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Bearing Estimation of Military Targets Using Single Seismic Sensor

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ABSTRACT

Using a single three-axis seismometer it is possible to provide bearing estimates to military targets. This has traditionally been done with large interconnected arrays of seismic or acoustic sensors. This technique lays the groundwork for cheap low power sensor nodes to provide bearing estimates to targets. Such sensor nodes become ideal cueing devices for other collocated or remote sensors in a sensor network.

1. INTRODUCTION

There is a growing interest in the development of distributed microsensor systems that will be used for reconnaissance, surveillance and target acquisition operations. These systems will be called upon to detect, classify, identify, and locate targets of interest under a variety of environmental conditions. To optimize performance under varying conditions a variety of sensors, including seismic, acoustic, magnetic, imaging, and others, may be used. Each of these having it's own strengths and weaknesses. It is desired that these systems be small, inexpensive, and have long operational lifetimes. All of these systems will contain sensors, signal processors, communication links, and power sources. Communication of data or information is perhaps the largest consumer of energy, so to improve sensor lifetime the amount of data to be transmitted must be minimized. To achieve this as much processing must be done locally as possible. Seismic sensors provide a very nice complementary capability to acoustic sensors, which fail under some environmental conditions such as wind and heavy rain. Beam forming, or target localization, using seismic sensors has traditionally been done using distributed arrays of sensors where the raw sensor data must be collected at a central processing node or facility. This necessitates a large amount of communications bandwidth and precise knowledge of sensor locations. By using a three-axis seismic sensor co-located with an acoustic array it is possible to perform beam forming within a single node under a variety of environmental conditions with no communications overhead for only a small increase in local signal processing load. Furthermore it is possible to fuse the data from these two sensing modalities to achieve better detection, classification, identification, and localization than is possible using either sensor alone. Fusing these data with other sensing modalities will yield even greater benefits.

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2. USING A SINGLE THREE-AXIS SEISMOMETER

It is possible to provide bearing estimates to military targets using a single three-axis seismometer. The seismic wave propagating from the target will cause a response on each of the two perpendicular, horizontal axes that is directly related to the angle of approach of the wave. Thus, the response of these two axes can be seen as forming a vector pointing back at the target. An estimate of the bearing of the target can therefore be calculated by taking the arctangent of the ratio of the responses of these axes. For instance, given that an axis' response over time is zero mean, a simple method might take the arctangent of the ratio of the standard deviations of the responses of the axes for some reasonable amount of time, based upon some expected angular velocity and based upon some given random noise floor. The method we have used utilizes the covariance matrix of the two perpendicular, horizontal axes and is based upon work done in the nuclear event detection arena[1]. Utilizing the covariance matrix is a more sophisticated way to eliminate poorly correlated background noise, since this noise will show little covariance between the axes, whereas the response to the seismic wave propagating from the target will show a great deal of covariance.

3. DATA COLLECTION AND BEARING ESTIMATION

Our data was taken on Spesutie Island at Aberdeen Proving Ground in Maryland[2]. The data was taken of a light tracked vehicle moving on an asphalt path at 25 kilometers per hour. The three-axis seismometer was placed 50 meters from the path. The seismic data was collected at a sample rate of 1024 samples per second. GPS data was also collected.

For each 1024 points (one second), our method calculates the covariance matrix of the two perpendicular, horizontal axes of the three-axis seismometer and then calculates the maximum eigenvalue of this covariance matrix. The maximum eigenvalue can be seen as the variance of the vector pointing back at the target. We then take this maximum eigenvalue (λ) and subtract from it the variance of one of the axes (σ_1^2). We then take this difference and divide it by the covariance of the two axes (σ_{12}). We then take the arctangent of this ratio to get an estimate of the bearing of the vehicle (ϕ). The mathematical derivation on which this method was based can be found in the paper in reference one. To summarize:

$$\phi = \tan^{-1}((\lambda - \sigma_1^2)/\sigma_{12})$$

Our algorithm was implemented in MATLAB. Using this method, we were able to track the bearing of the vehicle out to a distance of approximately 700 meters with reasonable accuracy.

Figure 1 shows the distance from the seismometer to the vehicle based upon our GPS data.

FIGURE 1 -- DISTANCE FROM GPS

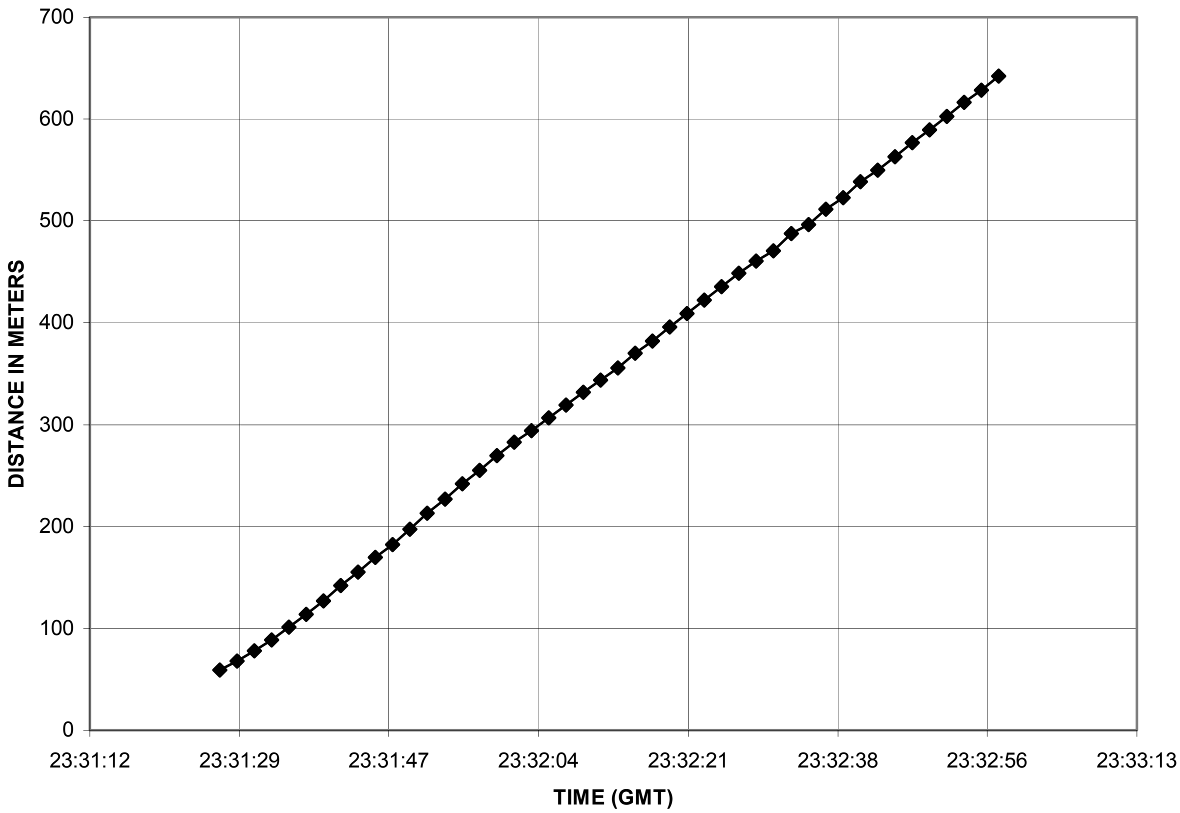


Figure 2 shows the bearing of the vehicle based upon our GPS data. The angle is counterclockwise from due west.

FIGURE 2 -- BEARING FROM GPS

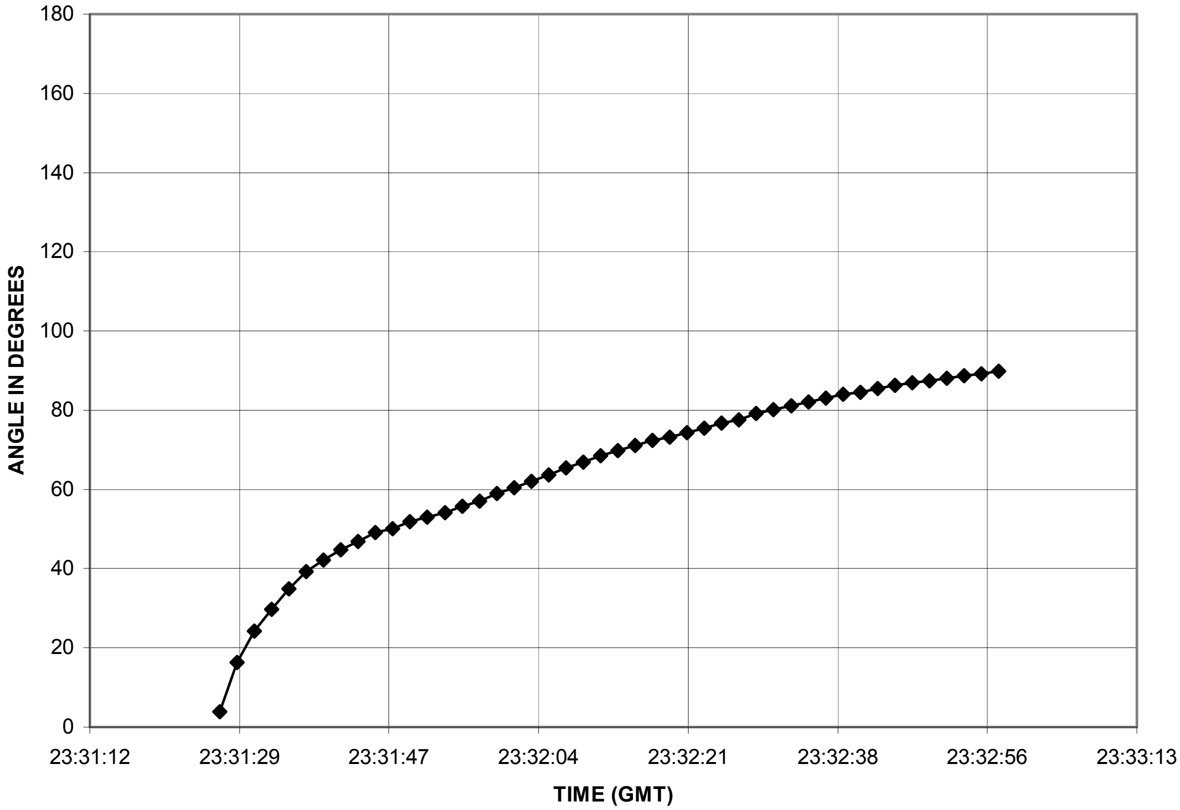
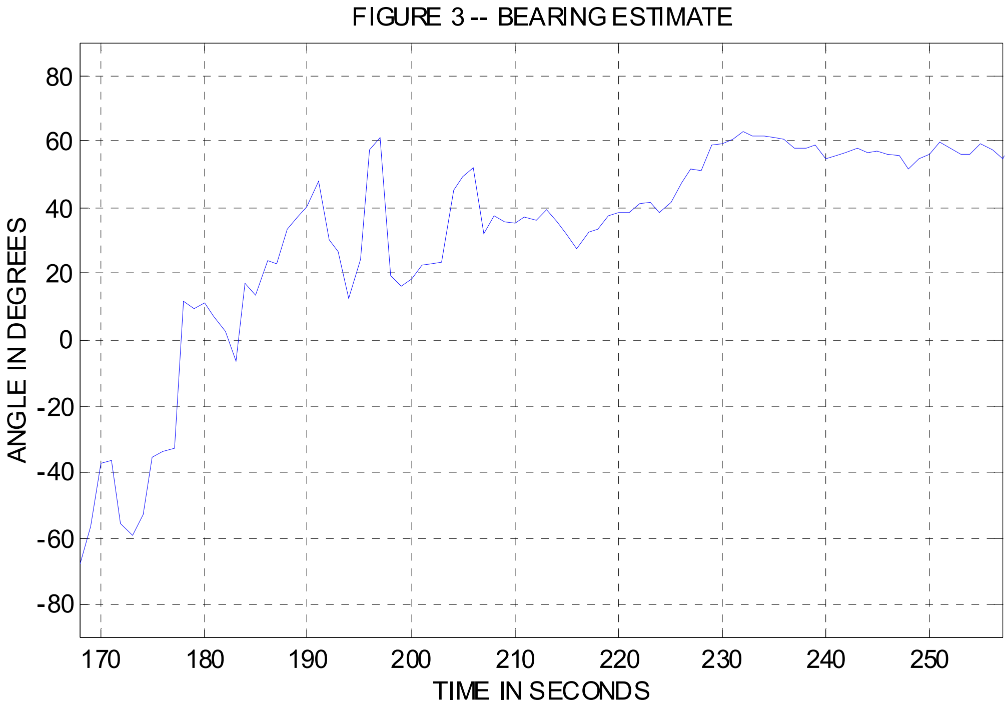


Figure 3 shows the bearing estimate of the vehicle based upon our algorithm. It should be noted that the seismometer was not latitudinally aligned, which accounts for the offset with respect to the GPS bearing.



Figures 4 and 5 show the spectrograms for the two perpendicular, horizontal axes of the seismometer. A particularly strong band can be seen around 80 Hertz.

FIGURE 4 -- SPECTROGRAM FOR FIRST AXIS

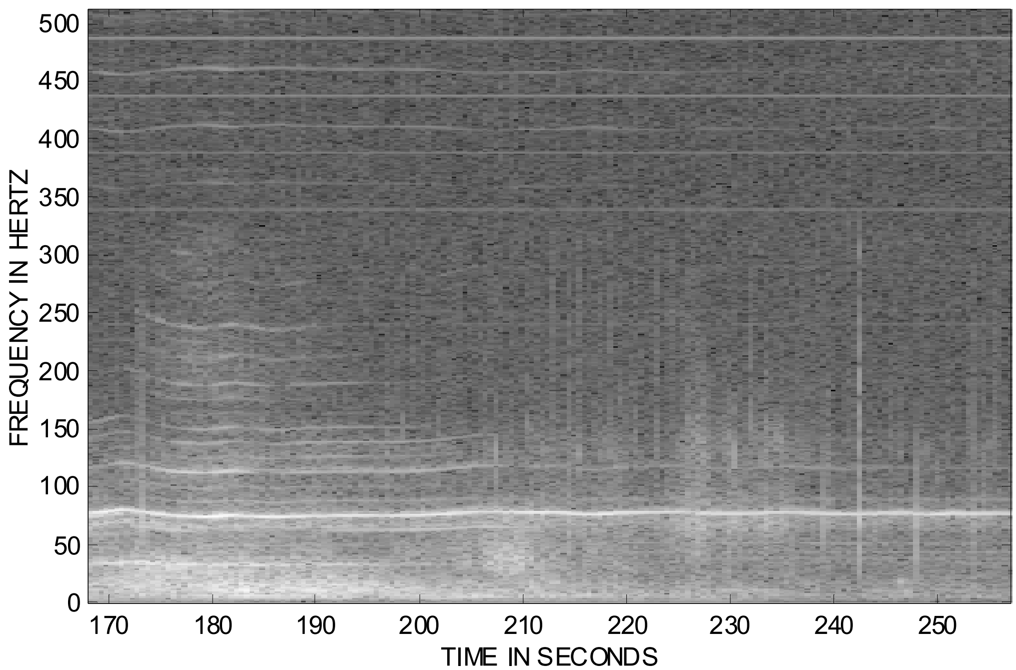


FIGURE 5 -- SPECTROGRAM FOR SECOND AXIS

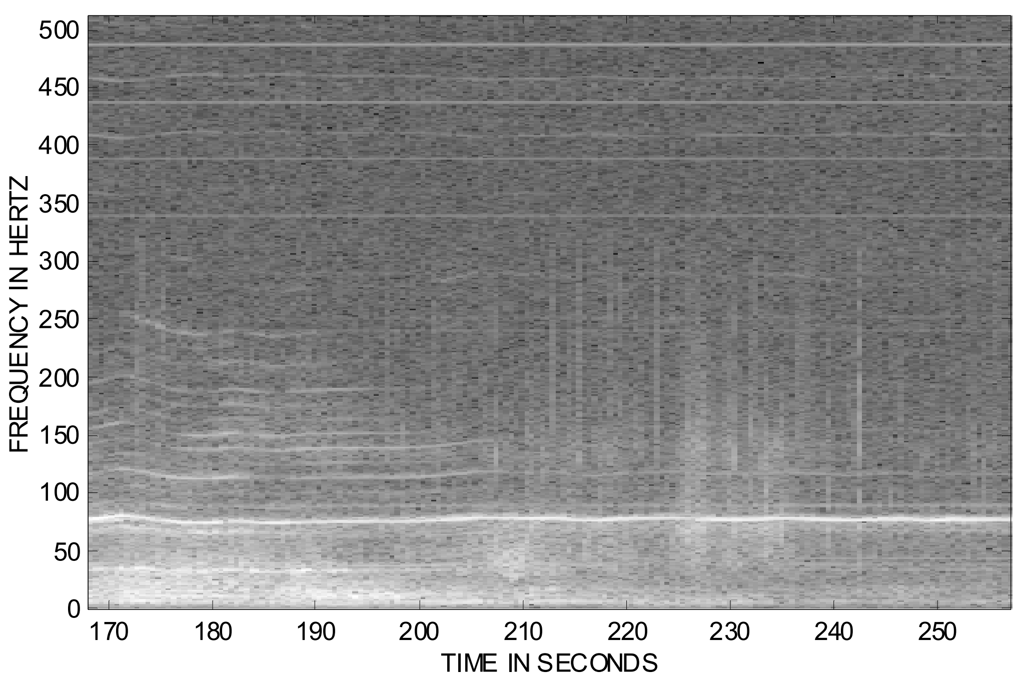
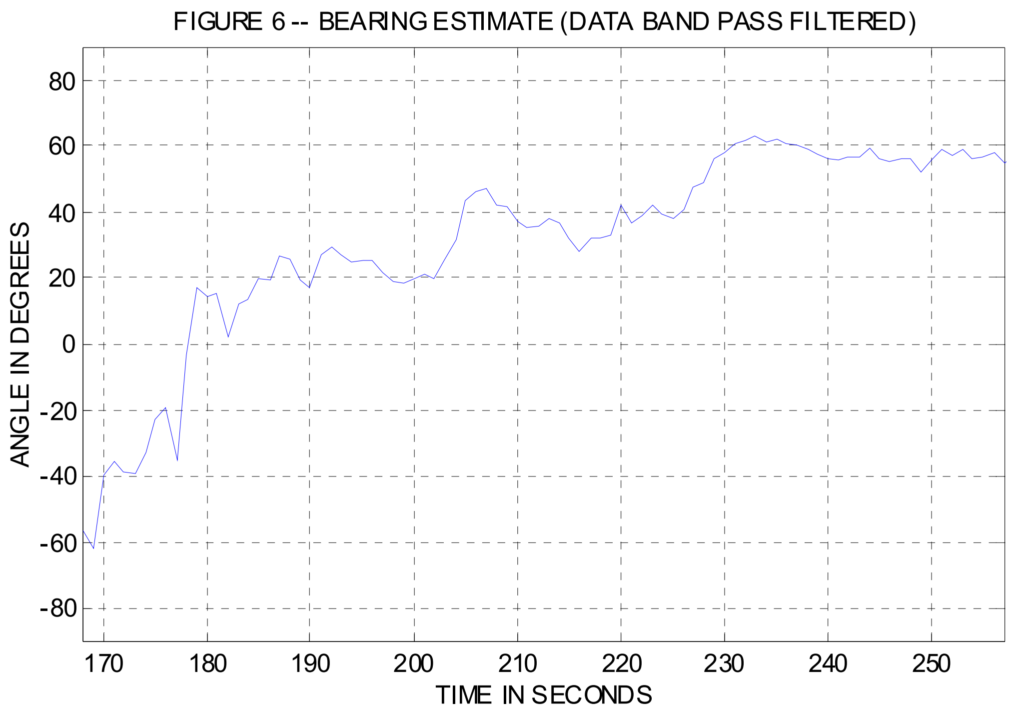


Figure 6 shows the bearing estimate of the vehicle based upon our algorithm after a 50 to 100 Hertz FIR filter has been applied to the data. The filtering cleans up the bearing estimate considerably.



4. ANALYSIS AND CONCLUSIONS

Our data shows that reasonable bearing estimates can be provided for military vehicles from a single three-axis seismometer. A method based upon utilization of the covariance matrix of the two perpendicular, horizontal axis produced good results. Further thought should be given to the practicality of using spectral analysis in real time, given the improved estimates obtained by band-pass filtering the data prior to applying the algorithm. The filtered data was accurate to within a few degrees most of the time and was almost always accurate to within about 10 degrees.

It should be noted that while there may be various other ways to handle the 180 degree ambiguity inherent in our method (per reference one), the simplest way initially might be based upon knowledge of which hemisphere the target is expected to occupy (for instance, the hemisphere containing some road). We do plan to look at the possibility of using the vertical axis of the three-axis seismometer to help resolve this ambiguity.

It should also be noted that our method did not produce useful results for other sections of the asphalt path (including that section most close to our seismometer), possibly due to underground structures. We intend to further investigate that scenario.

Future work will also focus on the scenario of more than one target and the possibility of adapting our approach to utilize specific frequency bands that might help separate various targets. We also want to compare the results from two separate three-axis seismometers, where one is turned 45 degrees with respect to the other -- this would help us evaluate any noise-induced uncertainty in the algorithm at any point in time when the seismic wave is impinging on only one of the two perpendicular, horizontal axes (i.e. at 0 and 90 degrees).

5. ACKNOWLEDGMENTS

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6. REFERENCES

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2. L. K. Sim, D. H. Gerstman and V. A. Nguyen. The Distributed Unattended Networked Sensors Field Experiment. Army Research Laboratory Memorandum Report ARL-MR-485, November 2000.